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TECHNICAL REPORT

Identification and Validation of Reference Events within the Area Regionally Monitored by IMS Stations in Asia and North Africa

October 2004

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13. ABSTRACT *(Maximum 200 words)* A database of seismic networks and stations, including their operational history, has been compiled from all sources. In particular, the name, coordinates and elevations of seismic stations that have operated or are presently operating in Iran, India and China have been compiled. Seismic stations that have a long history of reporting phase data have been identified and validated. A new groomed version of the ISC/NEIC bulletin database for the period 1964-2000 has been used to identify and investigate potential reference events that meet GT5 criteria. A new algorithm that uses the new station database to identify potential reference events meeting GT5 criteria based solely on the distribution of potential reporting stations has been developed and implemented. High-resolution cluster analysis has been refined and applied to known earthquake sequences and to nuclear explosion sites in Asia and North Africa for which one or more of the associated events is known to GT5 accuracy. Visits by scientist from China, Iran and India have enabled us to identify new sources of reference events in those countries and to familiarize them with applications of the Hypocentroidal Decomposition (HDC) method. Regional arrival time data for stations in those countries for the Lop Nor, Chamoli and Bhuj clusters was obtained. A well-located GT5 data set of explosions and earthquakes was used to develop epicenter accuracy criteria for near-regional, regional, and teleseismic distance ranges. The cluster event catalogs and derived parameters, such as empirical estimates of source-station path anomalies, has provided a reference data set that has been used in experiments designed to validate a 3-D model of the region of interest.			
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SUMMARY

The primary objective of our research efforts was to assemble a comprehensive, ground truth, event database with validated travel-time information for regional seismic phases recorded by IMS and surrogate stations in Asia and Africa. We have developed high-resolution cluster analysis (multiple-event relocation) of earthquakes and other seismic sources as a tool for assembling catalogs of ground truth events, especially those whose locations can be determined with an accuracy of 5 km or better. We have used the Hypocentroidal Decomposition (HDC) method of Jordan and Sverdrup (1981), that is particularly well suited to the rigorous statistical analysis required for this task. Candidate ground truth earthquakes typically came from local seismic networks and from temporary deployments for aftershock monitoring, yielding very high-resolution hypocenters that, nevertheless, must be validated. We utilized (primarily) phase arrival-time data reported to the ISC and the NEIC at regional and teleseismic distances in our HDC analysis to validate candidate ground truth events, and in some cases, to generate new ground truth "promoted" events. As a result, we have assembled a data set of nearly 1000 events across Eurasia and Africa of magnitude 3.5 or greater, including defining phases, whose locations and origin times are known with uncommon accuracy.

Our initial work with candidate "ground truth" events suggests that considerable care must be taken to ensure reliable results. Many aftershock studies and temporary seismograph deployments in remote areas suffer from logistical, operational, and analytical difficulties that may compromise the quality of the computed locations. Such problems are seldom apparent in published papers and abstracts. In many cases it will be necessary to gain access to raw data and analysis records—and most importantly, to gain the cooperation of the original researchers—to confirm the reliability of ground truth (GT) events offered by the seismological community in these regions.

The Hypocentroidal Decomposition method of multiple event analysis has proven to be very well suited to the requirements of ground truth validation exercise, but we have also found a number of areas in which additional development of the method is needed. Enhancements to the algorithm are needed to implement a more appropriate statistical model for reading errors and for dealing with outliers. A statistically rigorous procedure for optimally matching the HDC cluster with ground truth event locations is needed. Further research is also needed on some aspects of the application of the HDC method. For example, we need a better understanding of how to choose a minimum epicentral distance for data to be used in HDC analysis, and a better protocol for deciding how large a cluster may be without compromising the analysis.

The resulting data set of nearly 1000 events across Eurasia and Africa, with locations and origin times known to uncommon accuracy, were used to calculate empirical source-station path corrections relative to the Earth model ak135 (Kennett et al., 1995) for regional seismic phases recorded by IMS and surrogate stations in the region of interest. These ground truth events, which occur in event clusters, the groomed P and Pn arrival time data observed at regional distances (distance < 20 degrees), and about 1000 empirical phase path anomalies that are constructed from each of the clusters, create a GT data base that was used to assess the quality of 3-D models and their applicability to regional locations.

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY →	BY →	TO GET
TO GET ←	BY ←	DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_K = (t^\circ f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

The term "ground truth" is used rather loosely in the seismic monitoring community. It implies an exceptionally high level of confidence in source location and origin time, which can normally only be found in man-made explosions. The common usage of "ground truth" within the monitoring community, however, implies a similar level of confidence in the accuracy of locations of earthquake sources by local seismic networks. It is well known, however, that the formal estimates of uncertainties in local network processing can be misleading, being based on the assumption of Gaussian, zero mean, uncorrelated error processes. These assumptions are seriously violated in many local network catalog locations, leading to location bias and the underestimation of true location error, especially at high confidence levels. In our work on this subject, we have often encountered "ground truth" data from local seismic networks, which was in fact significantly biased from a variety of causes. In the most extreme case we have yet encountered, Iranian colleagues provided a "ground truth" location for one of the aftershocks of the 1997 Ghaen-Birjand earthquake that was mislocated by over 100 km, due to gross errors in phase association and poor station coverage.

In a recent study, Bondar et al. (2003) established reliable, conservative probabilistic estimates for local network epicenter accuracy based on station geometry. They developed local network selection criteria from explosions with exactly known epicenters and used a Monte Carlo simulation to validate these criteria. For local networks (0–2.5°) they found that candidate events at the $GT5_{95}$ confidence level must be recorded by at least 10 stations within 250 km, have a primary azimuthal gap of less than 110°and a secondary azimuthal gap less than 160°, and have at least one station within 30 km from the epicenter. We have used these criteria in our research, as well as detailed analysis (including relocation) of the original local network data, to ensure the highest possible confidence in our "ground truth" data set.

The development of high-quality, ground truth data sets with validated travel-time information for a wide range of seismic phases over regional and teleseismic paths is a powerful and direct method to address the problem of uncertainties in event location is. Such data sets can be used to support the calculation of regional travel-time curves and develop empirical corrections using statistical techniques, such as Bayesian kriging (Schultz et al., 1998; Myers and Schultz, 1999). They can also be used to characterize the systematic nature of mislocations in different regions and to identify regions where calibration experiments are necessary.

Several groups besides the University of Colorado have been working to create ground truth data sets. LLNL is working as part of the DOE effort to validate and integrate the efforts of academic groups into the Knowledge Base, so that US monitoring agencies can make use of this information (Schultz et al, 2000). Both efforts have led to the recognition of the critical importance of *validation* of proposed ground truth events. A seismic event is proposed as a ground truth event on the basis of certain aspects of the arrival time data used to locate it, such as the number of stations used, number of defining phases, nearest station distance, and open azimuth. General relationships between such characteristics and the uncertainty of the resulting location have only recently been developed (Bondar et al., 2003).

Validation through critical examination of the data and procedures that were used in the local network location of a proposed ground truth event is an *internal* process. It is certainly of great value, and in some cases, adequate to guarantee ground-truth levels of accuracy. In many cases, however, an internal validation process is highly susceptible to unavoidable uncertainties in the arrival time data and the local velocity structure. For example, there can be undocumented timing errors in the local network, incorrect station locations, incorrectly picked or mis-associated arrivals, and unrealistic estimates of reading error. A very difficult problem in many regions is the specification of a sufficiently accurate velocity structure for the local network location. Investigators rarely have enough information to control all these factors in a validation exercise, and a certain amount of faith is ultimately required in adding such events to a ground truth data set.

Therefore, an *external* validation process, one that utilizes other information as a crosscheck on the reported local network location, is highly desirable. Our experience has shown that many candidate ground truth events fail to pass even a cursory external validation test. An example comes from eastern Iran, concerning the 1997 Ghaen-Birjand earthquake. We made contact with the Iranian seismologist who had conducted the aftershock survey as part of his Masters thesis, and obtained what appeared to be a good, ground-truth event data set from him. Under HDC analysis, however, we found that many of the events had been mislocated, for unknown reasons. It appears that some events were actually outside the aftershock network, but were somehow mislocated within it.

We have used Hypocentroidal Decomposition (HDC), a powerful algorithm for multiple event relocation, as a tool for discovery and validation of ground truth events. Currently, HDC is one of the very few methods available to independently test proposed ground truth events. It therefore deserves a thorough and systematic development for this important task. HDC is applicable in situations in which several candidate ground truth events are located in a limited region, and in cases where other seismic activity in the area can be localized to known faults and other geologic features. The essence of the validation process is to compare the relative locations in space and time of events based on their ground truth locations, and the relative locations revealed by HDC. Because of the high seismicity rates and rapid growth in the number of seismic stations, networks, and temporary deployments in the study area, opportunities of this sort have been increasingly common.

SECTION 2

METHODS AND PROCEDURES

2.1 Motivation.

Basic research is called for in the field of seismic calibration in order to enhance US capability to globally monitor nuclear testing. It is expected that the results of these research efforts will be validated and rapidly integrated into the Department of Energy Knowledge Base where they may be used to strengthen operational monitoring. In this way, the research addresses US needs for improved monitoring capability. High quality, seismic calibration information contributes to this goal because of the large number of seismic events that will be detected as monitoring thresholds are reduced and seismic location comes to depend on fewer, higher-quality data.

Basic research questions are motivated by the operational challenges of enhancing seismic monitoring capability and, in particular, of reducing and accurately characterizing the systematic error of event locations. Accurate seismic calibration information is essential for this purpose.

The value of ground truth event data sets is seriously diminished if it is understood that there are significant numbers of bogus entries, or entries which do not meet the advertised criteria, yet there is no obvious way to tell which entries are problematic. The users of ground-truth event data sets should not be expected to perform quality control on them; they are expected to take the database as a baseline for validating their own research results. It is therefore crucial that validation tools be developed which can be used during the assembly of ground-truth event data sets to cull bogus events. In extreme cases, these tools may be called on to help resolve important cases of contradictory results involving ground truth events.

2.2 Network and Station Information.

We have assembled and vetted a database of information (e.g., name, coordinates, elevation, operational history, etc.) from all sources about seismic networks and stations that have operated in the study region. We have used this database to determine the coverage and operational history of each network as a function of time. A goal of this effort was to isolate the periods of time when these networks could potentially provide locations for earthquakes of magnitude greater than 2.5 to an accuracy of 5 km or better (and corresponding accuracy in origin time and depth). In particular, we have received from reliable sources the name, coordinates and elevations of all seismic stations that have operated or are operating in Iran, Kyrgyzstan, India and China. With techniques developed by Engdahl and Ritzwoller (2000) we have identified and validated all seismic stations having a long history of reporting phase data that are co-located or near IMS stations in Asia and North Africa.

2.3 Arrival Time Data.

In developing ground truth databases we have depended almost entirely on arrival time picks reported in the catalogs of international agencies, such as the International Seismological Centre (ISC) and the U. S. Geological Survey's National Earthquake Information Center (NEIC). While these picks have proven to be quite useful in the analysis of clustered ground truth events, where the statistical properties of source-station path anomalies can be determined, reading errors are often large and, of course, the picks cannot be confirmed. This deficiency can only be addressed by expanded analyst review of relevant waveforms that can be acquired for ground truth events in all countries within the study region.

We have completed our investigation of potential reference events, especially several unique event clusters in Asia and North Africa, identified using a new expanded and groomed version of the ISC/NEIC bulletin data base for the period 1964-2000 (Engdahl et al., 1998). A new algorithm that uses the new station database to identify *potential* reference events meeting GT5 criteria based solely on the distribution of *potential* reporting stations has been developed and applied to events in Iran and China. Potential reference events that have been identified in the Iran region based on a station database that includes known Iranian stations are shown in Figure 2-1.

GT5 Candidate Events in Iranian Region

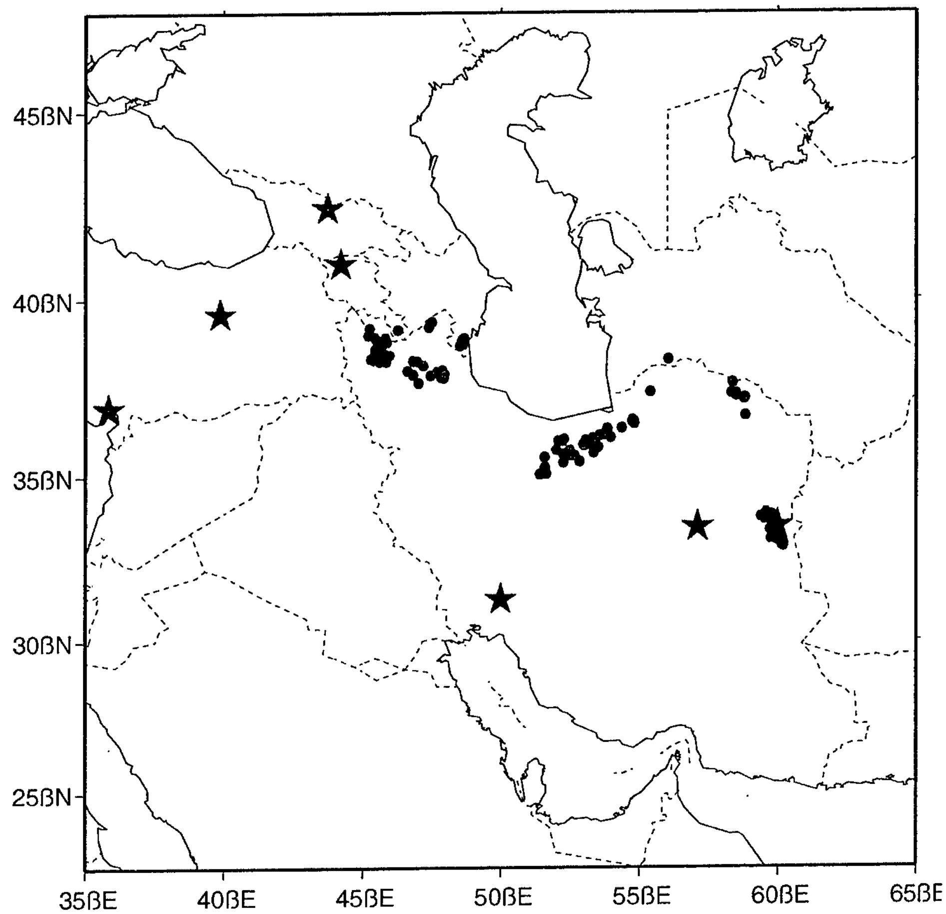

Figure 2-1. Potential events (red circles) and clusters studied (blue stars) in Iran region.

2.4 Location Algorithms.

Our work on the collection of ground truth data has proven the importance of applying a validation process to candidate ground truth data sets. Our approach has been to investigate the consistency of the data on an event-by-event basis with a carefully conducted single-event location procedure based on the well-known EHB method (Engdahl et al., 1998), and then to make additional tests of consistency between events in the process of a multiple event relocation exercise using HDC. Results of the HDC analysis may reveal the effects of small-scale lateral heterogeneities (on the order of tens of kilometers) that may require (data permitting) further sub-division of the original cluster into sub-clusters for separate analyses. This is a proven approach that provides very high-resolution validated travel-time information throughout the region of interest for the construction of source-specific station corrections. It also permits the validation of events submitted by other sources and purported to be ground truth.

2.5 Hypocentroidal Decomposition.

Our research program for the discovery and validation of ground truth events utilizes an algorithm for multiple-event relocation known as Hypocentroidal Decomposition (HDC), a method first proposed by Jordan and Sverdrup (1981). Here we provide a brief summary of the method, its strengths, and the current mode of application for validation work. The exposition closely follows that of Jordan and Sverdrup (1981), but, of necessity, it bypasses many details.

Like all methods of multiple-event relocation, HDC exploits the observation that the noise contaminating travel times from a set of clustered seismic events tends to be strongly correlated. Posing the problem in such a way that the differences in travel times are used in the inversion provides enhanced resolution of the relative locations of the clustered events. The error process of the relative event location is represented by

$$\hat{E} = \Delta\hat{T} - \hat{B} \bullet s - \hat{A} \bullet \Delta X \tag{2.1}$$

where $\Delta\hat{T}$ is the set of travel time differences, normalized by the standard deviation matrix $\hat{V}_n^{1/2}$, $\hat{B}$ is a partitioned matrix of zeros and ones, which associates path (station) corrections s with individual residuals. The third term on the right side of the equation represents the contribution to travel time differences of the relative locations, relative to some reference point. $\hat{A}$ is a partitioned matrix of partial derivatives and ΔX carries the relative location information. The solution is found by minimizing the squared norm of the error process, through application of the generalized inverse to the bias-corrected residual vector:

$$\Delta\hat{X} = \hat{A}^{\dagger} \bullet (\Delta\hat{T} - \hat{B} \bullet s) \tag{2.2}$$

The HDC algorithm is based on a particular decomposition of the error vector $\hat{E}$. The set of location perturbations for $\boldsymbol{P}$ cluster events is decomposed as:

$$\Delta x_p = \Delta x_o + \delta x_p$$

where

$$\begin{aligned} \Delta x_0 &\equiv P^{-1} \sum_{p=1}^{P} \Delta x_p \\ \sum_{p=1}^{P} \delta x_p &= 0 \end{aligned} \tag{2.3}$$

The quantity $x_0 + \Delta x_0$ is called the ***hypocentroid***, and $\{\delta x_p\}$ are the ***cluster vectors*** of the group. Furthermore, HDC identifies two projection operators (matrices), $\boldsymbol{P}_H$ and $\boldsymbol{L}_H$ that specify the decomposition of the relocation vectors into a *unique* hypocentroid vector and a *unique* cluster vector:

$$\begin{aligned} \Delta X_0 &= P_H \bullet \Delta X \\ \delta X &= L_H \bullet \Delta X \end{aligned} \tag{2.4}$$

where the capital variables are adopted for convenience to incorporate the equivalent arrays for the individual cluster events. Next we consider the equivalent decomposition of the error vector, through complimentary projection operators $\boldsymbol{P}_B$ and $\boldsymbol{L}_B$:

$$\begin{aligned} \hat{E}_H &= P_{\hat{B}} \bullet \hat{E} \\ \hat{E}_C &= L_{\hat{B}} \bullet \hat{E} \end{aligned} \tag{2.5}$$

Because $\hat{E}_H$ and $\hat{E}_C$ are orthogonal ($\hat{E}_H \bullet \hat{E}_C = 0$), the squared norm of $\hat{E}$ is the sum of two terms:

$$\left|\hat{E}\right|^2 = \left|\hat{E}_H\right|^2 + \left|\hat{E}_C\right|^2 \tag{2.6}$$

A considerable amount of manipulation leads to the simplified expressions:

$$\begin{aligned} \hat{E}_H &= P_{\hat{B}} \bullet \Delta\hat{T} - \hat{B} \bullet s - \hat{B} \bullet A_0 \bullet \Delta x_0 - P_{\hat{B}} \bullet \hat{A} \bullet \delta X \\ \hat{E}_C &= L_{\hat{B}} \bullet \Delta\hat{T} - L_{\hat{B}} \bullet \hat{A} \bullet \delta X \end{aligned} \tag{2.7}$$

that constitute the Hypocentroidal Decomposition Theorem. Because the path anomaly vector $\boldsymbol{s}$ does not appear in the expression for "cluster error", we solve first for the cluster vectors by minimizing $\left|\hat{E}_C\right|^2$. Then, using this estimate of the cluster vector in the expression for $\hat{E}_H$, we can solve for Δx_0 by minimizing $\left|\hat{E}_H\right|^2$. This step fixes the location of all the cluster events in map coordinates. This 2-step process is iterated several times and always converges quickly when the starting locations are reasonably good.

In comparison to other methods, HDC has computational advantages for larger problems and provides a completely rigorous application of all available "information" in the data set to the estimation of the cluster. There are no master events, no data is neglected, and the statistical model of the data is carried through the calculations rigorously. For these reasons, HDC is ideally suited to the monitoring environment in which statistical rigor is critically important.

Most other aspects of the relocation procedure follow closely the well-known EHB single-event location methodology of Engdahl, van der Hilst, and Buland (1998). In fact, we use a modified EHB procedure to screen cluster events and provide good starting locations. Travel times and derivatives are calculated using the AK135 model (Kennett et al., 1995) with ellipticity corrections according to Kennett and Gudmundsson (1996) and corrections for station elevation. Depths of all events are constrained by a careful EHB single-event analysis, combined with depth information from any ground truth events.

One area in which HDC departs significantly from EHB methodology is the characterization of reading uncertainties. We have recently begun estimating reading uncertainties for each station directly from the residuals of that station in the cluster analysis. In general this uncertainty is smaller than the standard assumptions used in single event location work because in the HDC analysis we have removed the contribution of correlated travel time errors. As a result, confidence ellipses are smaller and our confidence in the statistical validity of the results is raised. We are continuing to develop these procedures

Our future objectives with regard to HDC all lie in the area of achieving the optimal selection of data for analysis, better understanding the uncertainties of the results, and of handling the error budget as realistically as possible. We discuss the specific issues next.

2.6 Origin Time Normalization.

Origin time and depth resolution is – in general – poorer than resolution of epicenter parameters. The well-established trade-off between origin time and depth makes resolution of these parameters equally poor. Determining an absolute origin time is further challenged by potential errors in the average velocity model. Because we wish to use travel-time residuals from ground truth events, the potential for errors in origin time can become crucially important to calibration efforts.

For example, the origin times of two Hoceima, Morocco, ground truth events (m_b 5.5 and 4.6) released by DOE (Sweeney, 1998) were normalized to the reference model by 576 and 199 defining P picks, respectively. The Colorado groups' HDC analysis of 15 events (including the two ground truth events) was in good agreement with the relative positions of the ground truth locations. However, the HDC-derived origin times for these two events differed by 0.0 sec and -1.1 sec, respectively, from the individually normalized origin times reported by DOE. The large difference in the origin time shifts suggests considerable uncertainty in the origin time stemming from the different network of locating stations in the two studies.

As the Moroccan example points out, origin time estimates are sensitive to specifics of the locating network. These sensitivities are thought to result from changes in bulk travel-time prediction error caused by adding or deleting ray paths from the location process (Myers and Schultz, 2000). Therefore, neighboring events with different locating stations may have similar epicenter errors, but significantly different origin time errors. This situation is problematic for ground truth-event discovery and validation efforts, because the origin-time shifts increase travel-time residual variances and can hinder resolution of the sought-after signal. Normalization of origin times is also an issue in cases where clusters may be geographically localized by fitting a pattern of epicenters to known fault traces, but there is no ground truth information on true origin times.

While no solution to this problem is yet available (perfect knowledge of the source seems to be the only true solution), the most promising approach to minimizing it involves maintaining a consistent origin-time baseline for all events in a given cluster throughout the calibration and monitoring process. In future efforts we could carry out tests to place bounds on the likely level of uncertainty introduced by individual normalization of origin times, and recommend procedures to minimize it. For example, we could normalize origin times for an entire cluster using only arrival time data within a range of teleseismic distances for which the global scatter of observed travel times is especially small. These effects are probably best studied by close examination of cases where we have extremely dense station coverage at near distances, less than 50 km.

2.7 Shifting Clusters Using High-Precision Ground Truth.

The HDC process produces high-quality, relative locations and optimally locates the event cluster using regional to teleseismic data, but HDC-derived absolute locations are still subject to bias. We minimize the bias by shifting of clusters to match well-defined, ground-truth locations, whether from local network locations, fault geometry, or features derived from remote sensing data. In the past, we have simply averaged the offsets from cluster events to corresponding ground truth locations, which are assumed to have perfect accuracy.

2.8 Combined Uncertainties.

As discussed above, much of the power of the HDC method is that the relocation problem is completely separated, using orthogonal operators in model space, into an inversion for the 4-space cluster vectors relative to the hypocentroid, and the inversion for the absolute location of the hypocentroid. The location of the hypocentroid in geographic coordinates and UT fixes the absolute locations and origin times of the cluster events. The uncertainty of the location for any cluster event is therefore given in two parts, a confidence ellipsoid for the hypocentroid and the confidence ellipsoid describing the uncertainty of the cluster vector with respect to the hypocentroid. Hypocentroidal uncertainties are usually much smaller than those of the cluster vectors, and for many purposes may be ignored.

For the purposes of generating new ground truth events from HDC analysis, however, this convenient approximation is not appropriate and it is necessary to be able to combine these two aspects of location uncertainty to arrive at a single measure of uncertainty for an event that has been localized by HDC. In the clusters we have so far examined for ground truth event validation purposes, the semi-axes of the hypocentroid's 90% confidence ellipse are usually 1-3 km in length. This is not insignificant at GT5 levels of accuracy, nor even at GT10. As part of a general program to tighten up the statistical underpinnings of HDC for validation work, this issue must be addressed.

SECTION 3

RESULTS AND DISCUSSION

3.1 Ground Truth Event Clusters.

Under this contract, an expanded database of ground truth events of magnitude 3.5 and greater has been assembled, based on close analysis of a groomed ISC/NEIC phase database and seismic networks that have operated in the region of interest since 1964. The database contains a number of nuclear explosion clusters. Although ground truth information already exists for many explosions in these clusters, we have analyzed these clusters to both validate the reported ground truth locations and to estimate empirical station path anomalies for these sources. In most cases, ground truth event data for earthquakes were available from short-term portable seismograph deployments following the initiation of seismic activity. In this context, Hypocentroidal Decomposition (HDC) was used to enlarge the database with more recent events (especially those recorded by IMS stations) by co-locating recent events with nearby historical clusters containing at least one ground truth event that has already been validated. The HDC analyses produce new locations that are defined by "cluster vectors" in space and origin time, relative to the centroid which is then located in the traditional manner to yield absolute locations and origin times. If one or more ground truth events are included in the cluster, the centroid can be shifted to provide the optimal match to the ground truth locations, which brings all events in the cluster into close alignment with "ground truth". This approach thereby provides independent travel-time information for IMS stations *without knowing the ground truth location of the recent events.* The locations of ground truth event clusters analyzed under this DTRA contract are plotted in Figure 3-1 and the cluster parameters are listed in Table 3-1.

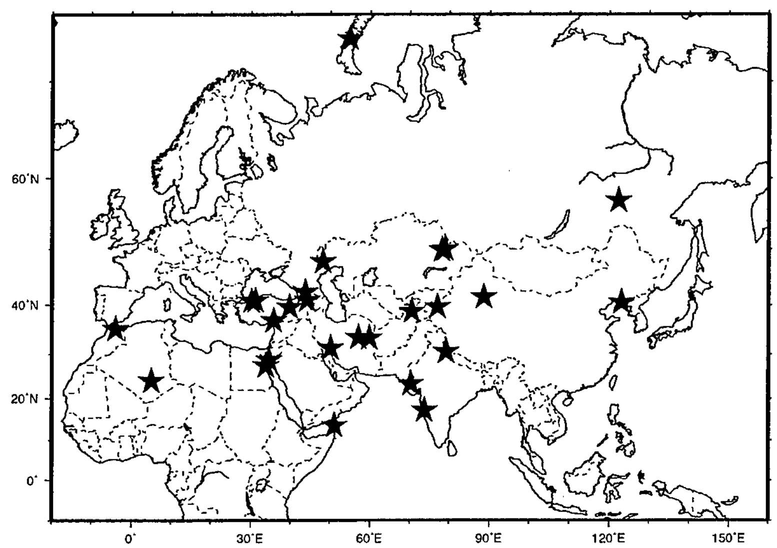

Figure 3-1. Locations of explosion and earthquake clusters studied indicated by stars.

Table 3-1. Cluster parameters for three categories of events: (1) explosions, (2) GT5 earthquakes, (3) GT10 earthquakes.

Cluster No.	Lat[a]	Lon[a]	Depth[a]	δt_o^b	nevt[c]	nref[d]	GTx[e]	Nam
1	47.875	48.139	.01	0.53	7	7	GT1	Azgi
2	49.954	78.871	0.0	0.81	100	100	GT1-2	Balap
3	49.784	78.072	0.0	0.66	151	146	GT1-2	Degel
4	41.580	88.605	0.0	0.43	20	13	GT1-2	Lop N
5	73.350	54.820	0.0	-1.65	29	28	GT1-2	Novay
6	24.049	5.040	0.0	-0.08	5	5	GT0	Sahar.
7	36.938	35.825	33.6	-2.89	24	4	GT5	Adan
8	23.486	70.265	19.6	0.36	107	6	GT5	Bhuj
9	30.590	79.124	12.1	-0.18	86	8	GT5	Cham
10	40.798	31.219	9.1	-0.64	41	2	GT5	Duzc
11	39.588	39.805	6.4	-1.73	9	3	GT5	Erzin
12	38.822	70.560	7.5	-1.55	28	4	GT5	Garm
13	35.235	-3.930	6.2	-0.91	38	3	GT5	Hoccin
14	40.740	30.223	10.4	-0.51	34	5	GT5	Izmit
15	17.236	73.748	8.2	-0.29	31	10	GT5	Koyn.
16	42.475	43.737	7.0	-1.28	35	5	GT5	Rach
17	57.092	122.276	31.5	-1.53	8	3	GT5	Siberi
18	13.513	51.069	10.0	-0.45	55	5	GT10	Aden
19	28.754	34.608	14.0	-1.94	36	1	GT10	Aqab
20	27.482	33.864	12.8	-1.49	27	1	GT10	Guba
21	39.660	76.988	19.06	-2.75	72	1	GT10	Jiash
22	40.957	44.215	5.6	-1.60	11	2	GT10	Spital
23	33.479	57.111	14.6	-1.95	35	2	GT10	Tabas
Explosions					312	299		
GT5 Earthquakes					441	53		
GT10 Earthquakes					236	12		
Total					989	314		

[a] Hypocentroid location, depth in km.
[b] Cluster time baseline shift applied to teleseismic and regional data, in sec.
[c] Number of GT events in the cluster.
[d] Number of refernce events in the cluster.
[e] 95% confidence in location accuracy better than x km.

There follows a review and evaluation of the clusters we have analyzed, which also are illustrative of some remaining problem areas. In particular, we find that some candidate ground truth events cannot be validated because either the reported local network solutions are in error or the coverage of reported arrival times used in the HDC analysis is not sufficient to constrain the locations. Some discrepancies may arise when local networks locate small precursors or low-energy early stages of rupture in larger earthquakes, while teleseismic stations record only the main pulse of energy release. We have found several cases in which there appear to be a systematic bias in the time base used for local network solutions. In another case, we obtained "ground truth event" locations from two different sources for the same cluster. The two sets are similar enough that HDC cannot be used to discriminate between them, yet different enough to prevent either set from being accepted at GT5 accuracy. Our experiences highlight the importance of a thorough and many-faceted validation program for candidate ground truth events.

Izmit, Turkey

There were dense deployments of temporary networks for both the Izmit and Duezce events which occurred along an extended fault system. From locations provided by A. Hofstetter (Geophysical Institute of Israel), we were able to identify 3 reference events in the Izmit segment of the fault sytem that included the mainshock and two large aftershocks. A cluster of 20 events resulted in 8 events of GT5 quality that are tied to only 2 of the reference events. The inconsistent shift vector and the early offset of the main shock origin time to the cluster result lead us to believe that the reported reference event was a small sub-event of the complex main shock which was not seen at regional distances. Accurate fault maps for the region may help to improve the resolution of these results.

Duezce, Turkey: An example of generation of ground truth events

This is a well-studied mainshock-aftershock sequence beginning on November 12, 1999, for which we were able to obtain 8 reference events, well recorded at regional and teleseismic distance, from studies made by Milkereit (2000) and Tibi (2001). A cluster of 32 events was formed from the mainshock and aftershocks through December 1999. We found very consistent shift vectors to the 8 reference events, resulting in 16 reference events of GT5 accuracy.

For this cluster Figures 3-2 through 3-4 show the progress in HDC analysis that leads to generation of new reference events. Figure 3-2 shows an early relocation of 52 events, before poorly located events are removed and outlier residuals are flagged. Figure 3-3 shows the final relocation of 32 well-constrained events. Figure 3-4 is derived from Figure 3-3, but shows only the 8 original reference events (black number), and 8 "promoted" reference events (red number) that meet GT5 criteria.

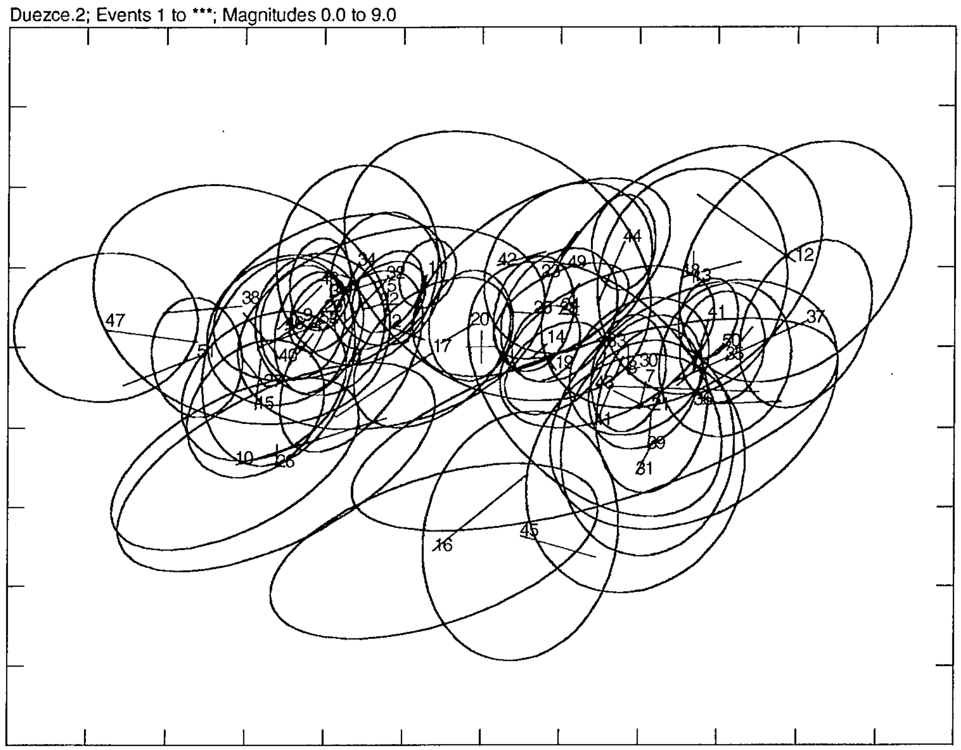

Figure 3-2. Relative locations of 52 earthquakes in the Duezce cluster from an initial relocation using the HDC method. Poorly located events have not yet been removed and outlier readings have not yet been flagged. Locations are relative to the cluster hypocentroid (red cross) at the center of the plot. Green vectors show the change in relative location from the EHB starting locations. 90% confidence ellipses for relative location are shown in blue. Tic marks are at 10 km intervals.

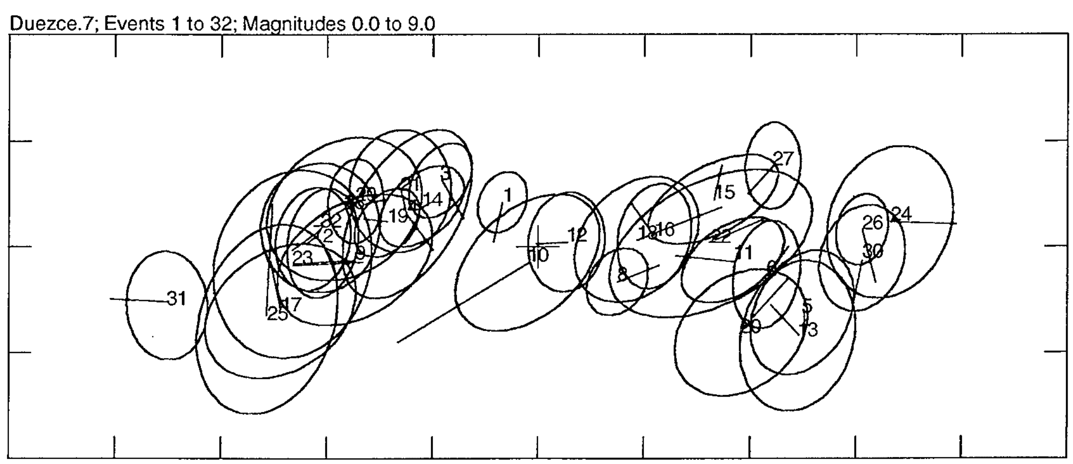

Figure 3-3. Relative locations of 32 well-constrained earthquakes in the Duezce cluster after outlier readings have been flagged.

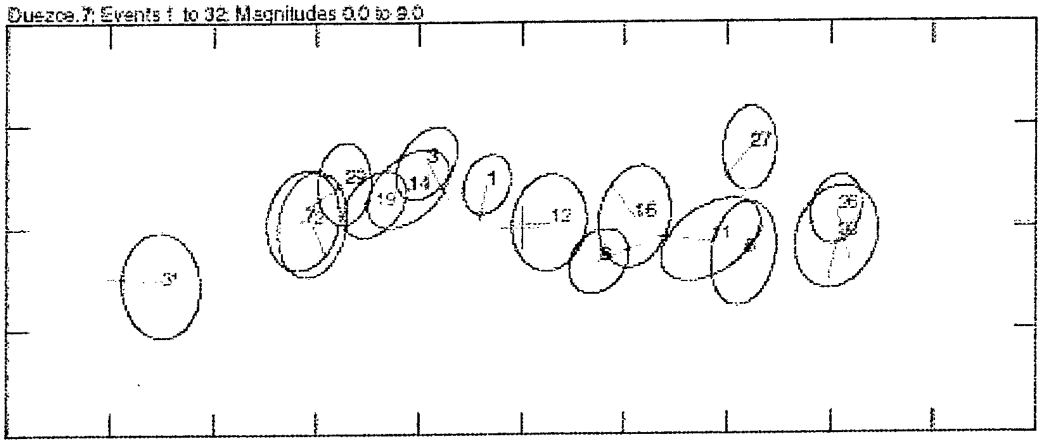

Figure 3-4. Same as Figure 3-3, but showing only the 8 original reference events (black event number) and 8 "promoted" reference events (red event number) that meet GT5 criteria.

Erzincan, Turkey

Three reference events were identified in the Sweeney report from a study by Fuenzalida *et al.* (1977a). The cluster events are from October 1976-April 1992 and included only 9 events. However, the reference events gave a consistent estimate of the shift vector as 9.0 km at 240°, -2.05 s in origin time which yielded 6 events with an accuracy of GT5 or better.

Adana, Turkey

Four reference events, determined using data from a local network, were provided to us by Rami Hofstetter (GII). These reference events gave a consistent estimate of the shift vector as 10.7 km at 79°, -2.89 s in origin time which yielded 24 events with an accuracy of GT5 or better. However, teleseismic depth phases suggest that the reference events are shallower than the 34 km centroid depth. This discrepancy cannot be resolved without being able to review the phase picks from original waveforms and relocating the events independently.

Zagros, Iran

This is a cluster formed of seismicity over a fairly large area of the Zagros Mountains, motivated by a report of three ground truth events by Asudeh (1983). The paper reported locations for three events in September 1976, based on a temporary deployment of seismic stations. But a careful reading indicates that the closest station to any of these events is at a distance greater than 150 km. Hence, the "ground truth" locations are probably no better than GT15. The HDC analysis for the cluster was very successful, yielding many events with relative locations at the GT5 level, so an effort to obtain true ground truth locations for a few events in the Zagros would be quite helpful.

Tabas, Iran

The cluster of 35 events is based on the aftershock sequence of the Tabas-e-Golshan earthquake of September 16, 1978, in eastern Iran, plus additional events in the area through 1992. Berberian (1982) discussed the tectonic significance of the locations for hundreds of aftershocks, but the actual hypocentral data are contained only in his thesis. Referring to the thesis, only two events are part of the cluster of larger earthquakes that can be well located with the HDC method. Unfortunately, we discovered inconsistencies in these ground truth data. The thesis contains a master table of all events and a table of the "best-located" events, but the hypocenters of the two "ground truth" events are different in the two tables. Moreover, the locations from the master table are in significantly better agreement with the HDC results than the locations from the "best-located" table. Hence, we have used the latter events to shift the cluster, resulting in 12 ground truth events of (tentatively) GT5 quality. But the origin times also seem to be biased relative to the origin times resulting from the HDC analysis. We are investigating these issues with the help of Berberian.

Zirkuh & Dasht-e-Bayaz, Iran

This grouping arose from our study of the Zirkuh (Berberian et al., 1999) earthquake and aftershocks of May-November 1997. The main shock is near the north end of a long fault, and most of the aftershocks, including the ones reported by an aftershock study as "ground truth events", are in the southern part of the fault zone, as much as 100 km from the mainshock. However, several other large earthquakes have occurred near the northern end of the Zirkuh fault, where it intersects with the E-W trending Dasht-e-Bayaz fault (Berberian and Yeats, 1998). There were three major earthquake sequences in a three-week period from mid-November to early December 1979. We formed a cluster of larger events from these three sequences, the 1997 Zirkuh mainshock and a few of its aftershocks, and some individual events from other times, 36 events in total. Although there are no ground truth locations available for any of these events, we have placed constraints on the absolute location of the cluster by utilizing the geometric constraints of the Zirkuh and Dasht-e-Bayaz faults, which are orthogonal to each other. The main events have well-constrained strike-slip mechanisms so the requirement that the main shock epicenters locate on the main faults (whose surface ruptures were well mapped right after the quakes) provides a strong constraint on the location of the cluster. Sixteen of the events in the cluster satisfy GT5 criteria on location, although origin times are still unconstrained.

Zirkuh South, Iran

The bulk of the aftershocks for the 10 May 1997 Zirkuh earthquake in eastern Iran are in the southern end of the fault zone, and ground truth locations from an aftershock survey (M. Raeesi, MS Thesis, University of Tehran, 2000) are available for many of them. We analyzed a cluster of 42 events from the sequence (Figure 3-5) and found many inconsistencies between the HDC results and the "ground truth" locations. Upon a closer reading of the thesis and discussions with the author and his advisor, we believe that further analysis of the aftershock survey data will be required in order to generate true ground truth event locations. There were numerous logistical problems with the survey (which was in a remote and dangerous part of the country) that may have compromised the results. Also, the fact that much of the aftershock activity occurred as much as 100 km away from the main shock epicenter led to unfortunate deployment decisions. This is a good example of the need for a validation process for candidate ground truth events.

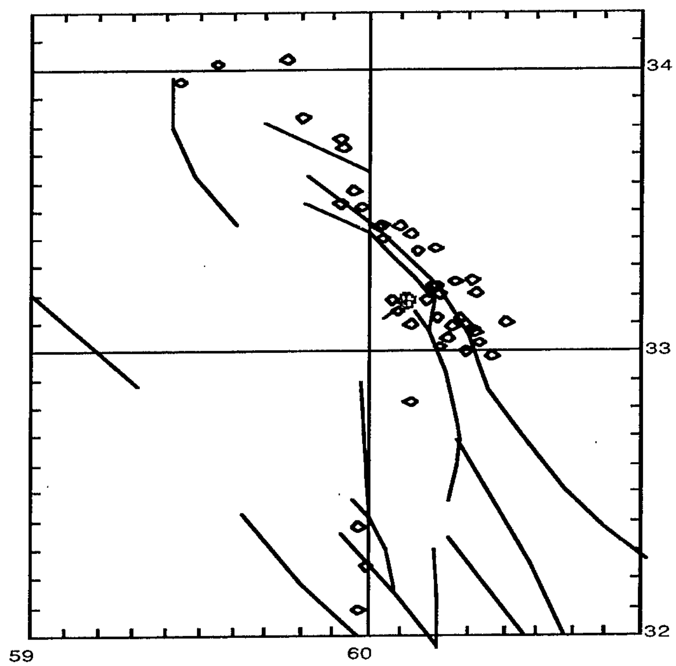

Figure 3-5. Map of the Ghaen-Birjand region in eastern Iran showing major mapped fault traces. Epicenters of 42 of the best-located events (area of 90% confidence ellipse less than 314 km^2, equivalent to a circle with 10 km radius) based on HDC analysis of the 1997 earthquake sequence are shown. Tics are 0.1 deg.

Koyna Dam, India

Ground truth locations have been obtained from a local seismic network installed to monitor induced seismicity at the Koyna reservoir in 1967. Many events greater than magnitude 5 have been recorded over the past few decades. We initially worked with a list of 17 ground truth locations from the National Geophysical Research Institute (NGRI). The first one is the original 1967 event (and of questionable reliability), but the rest are all between 1993 and 2000. We formed a cluster of 31 well-recorded events, and found very consistent estimates of cluster offset from nine ground truth events.

Chamoli, India

Proprietary locations from a temporary network provided 6 ground truth events that could be used in cluster analysis. The station azimuth gap for these solutions is less than 100 degrees and independent relocations using the same data are consistent. However, local data from other sources has yet to be integrated, so that our source conservatively estimates the accuracy of these events as GT5-GT10. A provisional cluster of 48 events yielded 20 events with an accuracy of GT5 based on the size of the HDC confidence ellipse. However, taking into account the uncertainty in ground truth event locations, we can only provisionally estimate the accuracy of these locations as GT5. Interestingly enough, this recent Chamoli sequence seems to have filled a gap where no previous earthquakes during the 1964-1999 period seem to have occurred.

Bhuj (Republic Day) Earthquake; Gujarat, India

Proprietary locations from an 8 station aftershock deployment that are considered accurate to +/- 1-2 km, as reported on at the 2001 SSA Meeting, have been made available to the project. However, integration of arrival time data from other deployments and permanent network stations operated by Indian institutions, as well as improvements to the local velocity model, need to be made before final ground truth event locations can be determined. Nevertheless, 6 of the 8 events from the proprietary data set were recorded well enough at regional and teleseismic distances to be included in a provisional Bhuj cluster. Results of a provisional cluster analysis of 51 events that included the Bhuj main shock and all of the larger aftershocks were quite consistent. HDC locations with respect to the 6 ground truth events were very systematic. Hence, the shifted HDC locations probably provide the only reliable source of information on the location of events in this sequence that occurred before any temporary networks were installed. In all, 16 of these locations were of GT5 quality, but further improvement can be expected with additional data. The earthquake sequence is unusual in that there is a wide range of depths (8 - 30 km), confirmed not only by local network hypocenters but by depth phases as well. Hence, a final piece of processing could be to assign (for events which were set at an optimal depth of 18 km) more appropriate depths as indicated by the distribution in space of the local network hypocenters.

Jiashi, China

This is a massive swarm in western China, beginning in January 1997, that was studied by a temporary deployment of seismometers. We formed a cluster of 83 events that are well located with HDC. Although we were provided with a list of ground truth locations from the local network that included most of the cluster events, we discovered a serious problem. Only one event had been well located by the network, and the remainder had been located with a master event method that was apparently misapplied, as the pattern of epicenters was in substantial disagreement with the HDC results. Moreover we found a very large difference (nearly 3 seconds) between the ground truth solution of the master event and the HDC results. This is too large to be plausible as a manifestation of the Earth's heterogeneity. We suspect that there is a problem with the time base used for these Chinese temporary deployments, as we saw a similar phenomenon with the Xiyuan cluster (below). Time-keeping problems might also explain why the Chinese researchers used the master event method. We have recently learned (Wu Zhongliang, personal communication) that the China Seismological Bureau is installing a temporary BB network around Jiashi to study this swarm, and we hope to obtain additional ground truth event data here. If so, we will be able to promote a large number of events to GT5 status as a result of the HDC analysis.

Xiuyan, China

The Xiuyan earthquake occurred in a region where the maximum intensity contours are so tightly constrained that the location accuracy of the main shock could be estimated by the Chinese as GT2. In addition, a local seismic network of analog and digital was being operated during a period that overlapped with the earthquake sequence. Four events reported by Xu (2001) were recorded well enough to be used as ground truth events and arrival time information to stations in China were provided to the project by Xu. Cluster analysis of 30 events across the aftershock region led to the following observations: (1) We cannot validate the ground truth event locations to any better than GT10 because either there are errors in these locations or the station coverage used in the HDC analysis is not sufficient to constrain our locations. In most cases, it is a combination of both of these problems; (2) Origin times indicated by our cluster analysis using regional and teleseismic data reported by ISC/NEIC are systematically about 4 sec later than the origin times of the ground truth events. Hence, the median path anomalies to all stations used in the cluster analysis are positive. Chinese seismological stations have timing synchronous with UNT with an accuracy better than tens of msec. Reconciliation of these origin time differences may be related to inconsistent time standards globally and needs to be investigated.

Lop Nor, China, Nuclear Explosions

Source parameters for Lop Nor explosions that are available from various sources appear to be conflicting. Hence, we decided to perform a careful cluster analysis of 20 events in 3 closely spaced source regions at the Lop Nor test site. All could be located to GT5 or better and all were tied to the origin times and locations (based on satellite imagery) of 4 events provided to us by Terry Wallace. These events gave us a very consistent estimate of the shift vector as 2.0 km at 289°, +0.82 s in origin time. Of the 11 events in common with Wallace's original JED analysis only 2 events differed by more than 2 km from his locations (94/10/07 at 2.5 km and 96/06/08 at 3.8 km). Of course, all of the origin times agreed to within 0.2 sec. We also compared our results to the JED locations published by Gupta (1995). Of the 13 events in common with his analysis 7 events differed by more than 2 km from our locations, with one differing by 7.7 km. Also, since he used the JB model for his analysis, his origin times were all about 2.5 sec earlier than ours were.

Eilat, Gulf of Aqaba

A list of candidate reference events came from the JSOP project, combining data from several networks in the area. The main events of interest were a large earthquake on November 22, 1995 and it's aftershocks. We formed a cluster of 37 events from this sequence and earlier events in the immediate area. As many as 13 events have been presented as reference events (Sweeney, 1998), but our validation exercise indicated numerous inconsistencies, probably because of the different organizations involved. Finally we kept only the mainshock on November 22, 1995 as a reference event (using a location provided by A. Hofstetter, Geophysical Institute of Israel). It was the only event whose location from local and regional data met the GT5 criteria and for which HDC analysis provides sufficiently strong location accuracy. The cluster was shifted to best match this location and a total of 12 events in the cluster were promoted to reference event status at the GT5 level. Efforts are ongoing to obtain additional data (especially from Egyptian stations) which might bring some of the other events in the area up to reference event status. This is one of the larger clusters we have used, extending about 100 km in the north-south direction, so it would be especially desirable to obtain additional reference events to ensure that the "common path" assumption for cluster analysis is not being violated.

Garm, Tajikistan

Reference events for this region are obtained from a dense local seismic network (G. Pavlis, Indiana Univ.). We formed a cluster of 23 events between 1975 and 1984. They are all well recorded at regional and teleseismic ranges and the HDC locations for most of them are close to or better than GT5. There are three good reference events, which give a consistent offset of the cluster. A fourth reference event was rejected because it was very inconsistent with the three others; either the HDC relocation or the reference location is bad. We will include additional events since 1984 to improve the station coverage and statistics.

Hoceima, Morocco

The reference events are part of a major swarm of earthquakes between 1994 and 1996. Most of the arrival time data for these events is at regional distances, however. Cluster analysis cannot be performed with such data, because it violates the assumption of common path errors. Our normal procedure is to use data only beyond 3°. In this case, the cluster includes only 15 events (from May 1994 to June 1996) which can be located at GT10 or better by HDC, but none of them qualify for GT5. The cluster is very tight, about 20 km by 20 km, therefore we could re-examine this cluster using data from shorter distances and include more events. Including more events would also improve the cluster vector statistics and reduce the size of the HDC confidence ellipses in some cases.

We used two reference events for this cluster, which were a revision of the locations reported by Sweeney (1998) and which gave very consistent epicenter shifts for the cluster. The difference in OT shifts between the two reference events was rather large, however, over a second. We learned subsequently that—because of timing problems in the network—the reported origin times for these reference events have been normalized (separately) by DOE to the ak135 reference model using reported regional and teleseismic residuals. Using this approach, the normalized origin time for each event becomes highly dependent on the stations reporting data for each event (576 & 200 stations). Therefore, although we can validate the 2 reference event locations, there is no independent information from this cluster on absolute travel times.

Racha, Georgia

The reference events come from a temporary seismic network (Fuenzalida et al, 1977b) that captured aftershocks of a large event in April 1991. The cluster events are from April-October 1991. The cluster included 47 events that could be located to GT10 or better. The cluster is elongated, about 70 km in an E-W direction, and composed of two sub-clusters. Some tests of relocating the sub-clusters separately were done, but we saw no evidence that smaller clusters improved the outcome. We used 6 reference events that gave a very consistent estimate of the cluster offset and 19 events of GT5 accuracy. We should be able to improve station coverage and statistics (and provide better coupling to IMS stations and surrogate stations) by adding more recent events to the cluster.

Sahara (Ahaggar Mountains), Algeria, Nuclear Explosions

This is a small cluster of 5 French nuclear tests in Algeria between 1962 and 1966 with reference event information published by Bolt (1976). As a validation experiment, we perform an HDC cluster analysis of the 5 events. The shifted HDC relocation is very good; the cluster is extremely tight, less than 10 km across; and we obtain a very consistent estimate of the shift vector, 5.6 km at 186°, -0.08 s origin time. The origin times are very close because these data were used with events elsewhere to set the baseline for the IASP91 travel time model. It is worth noting the arrival time data sources for these explosions: 620501 - ISS Bulletin: 631020 and 650227 - USC&GS Shot Report (most data read from original seismograms); and 651201 and 660216 - ISC Bulletin.

Spitak, Armenia

This is a small cluster of 11 earthquakes that are very well recorded at regional and teleseismic distances; the HDC locations are almost all better than GT5 quality in relative terms. The three reference locations are derived from a permanent regional network. The cluster consists mainly of an earthquake sequence in December 1988, with aftershocks continuing to May 1990, but there is also one event from January 1967 in the same area. This should have been an excellent ground truth resource, but the relative locations from HDC analysis are inconsistent with the reference locations. No two of the reference events are in agreement. Because of the very strong constraints on the HDC locations, we suspect a problem with the reference locations. As this cluster was formed from an active aftershock sequence, it may be that the local network and the global network (for HDC) are looking at different events which are nearly coincident in time, or the local network is picking up early low-energy precursors to larger events. Further investigation is required, possibly a review of waveform data.

Gulf of Aden

These are large events with CMT solutions, whose locations were obtained by a normal non-linear waveform inversion, but with the location constrained to a chosen bathymetric feature (Pan *et al.*, 2000). Cluster analysis provides a means of testing the accuracy of the constrained locations that have the potential for improving our understanding of regional variations in travel times. Probably the largest source of uncertainty comes from the choice of which feature to constrain the location to. This is not easy when there are many like features (ridges and transforms) close together. In addition, there is the problem of intraplate events that occur close to the plate boundary.

Cluster analysis of 55 events in this region that included 6 reference events from the Harvard compilation resulted in shifted HDC locations for 18 events with an accuracy of GT5 based on the size of the HDC confidence ellipse. However, since the location of the Harvard reference events is based on sea floor topography with resolution not better than 5 km, the GT5 shifted HDC locations can't really be much better than GT10 in the absolute sense. Most of these 18 events are on the transform segment of the cluster. However, one of the Harvard reference events moves away from the pattern of other nearby ridge-axis events and we suspect that this is actually an intraplate event close to the ridge.

Azgir, Kazakhstan, Nuclear Explosions

The HDC procedure is compared to the procedure of Joint Hypocentral Determination (JHD; Dewey, 1972, 1989) using seven closely spaced underground nuclear explosions near Azgir with ground truth information reported by Sultanov *et al.* (1999). In this comparison, as reported by Israelsson *et al.* (2001), HDC and JHD are applied to the same arrival time data to validate computational consistency of event locations and source-station travel time corrections, and to compare the scaling of error ellipses by the different data weighting of the two methods. The resulting HDC and JHD epicenters are generally consistent with a maximum separation of 1.7 km and with error ellipses that overlap ground truth within about 0.5 km. HDC and JHD error ellipses have slightly different orientations and ellipticity, and the JHD ellipses are on average slightly larger than HDC ellipses with the semi axes being about 10% longer. The median of the origin time differences is about 0.1 sec with a maximum difference of 0.2 sec. These analyses confirm that Sultanov's ground truth information for the Azgir explosions is self consistent. The arrival time data, which was provided from sources other than ISC/NEIC, provide especially useful regional travel times.

Balapan/Degelen, Kazakhstan, Nuclear Explosions

Coordinates for many of the nuclear explosions at the Balapan and Degelen test sites have been determined using a combination of LANDSAT and SPOT images (Thurber *et al.*, 1993; Thurber *et al.*, 1994; P. Richards, Lamont Doherty Geological Observatory). Origin times are also known very well on some of these events. An integration of these sources results in 100 explosions at the Balapan test site and 152 explosions at the Degelen test site that are of accuracy GT1 or better for which we have assembled the associated reported arrival-time data.

3.2 Validation Database.

The analyses of earthquake and explosion sequences in Eurasia and northern Africa has provided a database of groomed residuals for seismic events above mb~3.75 with minimal systematic error of event location. We used primarily phase arrival time data reported to the International Seismological Centre (ISC) and to the U.S. Geological Survey's National Earthquake Information Center (NEIC), or made available by other sources, that were groomed using a procedure described by Engdahl et al., (EHB; 1998). The resulting catalog and derived parameters in this database has provided a ground truth data set that can be used in experiments designed to validate 3-D models of the region of interest.

Such a 3-D model has been constructed from surface wave dispersion data by the University of Colorado (CUB) under DTRA01-00-C-0019, *Feasibility of the Use of 3D Models to Improve Regional Locations in Western China, Central Asia, and Parts of the Middle East* (Co-PI's M.A. Ritzwoller & E.R. Engdahl). S-wave speeds in the resulting 3-D S-wave velocity model of the Eurasian crust and the upper mantle were converted into P-wave speeds based on laboratory-measured properties of mantle minerals and an average compositional model of the upper mantle. The 3-D CUB model has been used in validation tests (Ritzwoller et al., 2002) that are briefly described below.

3.3 Model Validation - Station Path Anomalies.

Cluster source-station path anomalies have been estimated relative to the 1-D reference model AK135 for regional seismic phases reported by IMS primary and surrogate seismic stations, and other seismic stations in Eurasia and Africa. This is a rather straightforward process by which, for each cluster, all groomed residuals are examined for phases of interest (Pg, Pn, P, Sg, Sn and S) at each of the reporting stations in that cluster. Medians and spreads are calculated for all these phases and the resulting source-station phase path anomalies accepted when minimum requirements of five observations and a spread of less than 1.40 sec and 2.8 sec is met for P-type and S-type phases, respectively. Ordinarily, there are too few Pg phases in the database and the S-type phase residuals are too noisy to obtain any useful results for those phases. For the Pn and P phase path anomalies at all distances, however, we were able to successfully estimate 848 and 5176 source-station path anomalies, respectively. The results are plotted for the clusters studied over the regional distance range in Figure 3-6. These empirical estimates range from about -7.5 sec to +5.0 sec, with maximum differences occurring at distances of 11 to 18 degrees where the influence of interfering travel time branches makes phase identification difficult (see Figure 3-7).

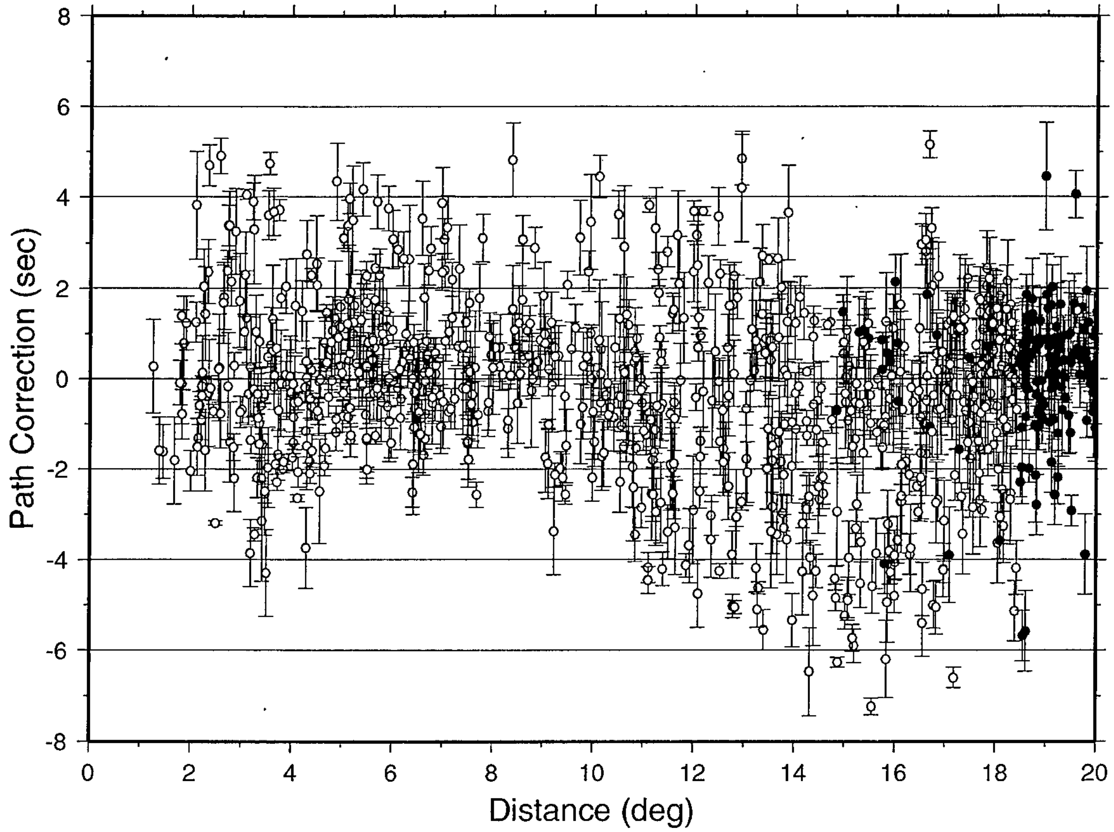

Figure 3-6. Reduced Pn (white) and P (black) empirical cluster phase path anomalies plotted as the median and spread estimates with respect to distance. Travel times are corrected for cluster time baseline shifts. Results are presented as residuals with respect to the AK135 travel times.

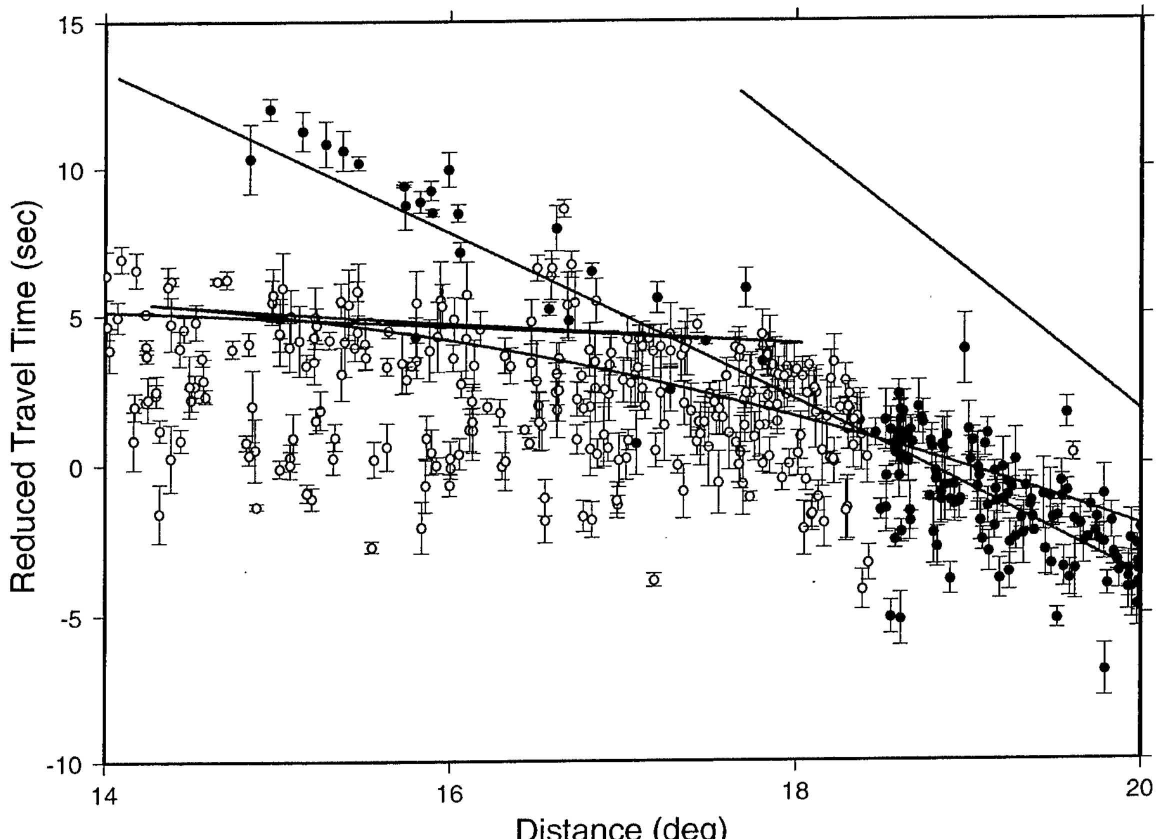

Figure 3-7. Same as Figure 3-6, except results are presented near the Pn/P cross over as reduced travel times (relative to 8.0 km/s). AK135 predicted Pn and P travel time branches are also shown.

Pn and P rays were traced through the 3-D CUB model described above to determine predicted travel times. These times were used to construct travel-time correction surfaces for the two phases. Empirically determined station path anomalies are plotted on this surface for the Lop Nor cluster in Figure 3-8. In general, the more robust features of the predicted correction surface match the empirical anomalies. However, in detail there are some differences that may be the result of fine scale deviations of the real earth from the CUB model (i.e., at the edges of its resolution) and/or shallow crustal structures). The correlation (0.75) of the P and Pn travel times predicted by the CUB model and the empirical path anomalies for all explosion clusters studied is quite good (Figure 3-9), largely the result of using an improved model. But this is also a result of using an automated phase re-identification (P or Pn) procedure that provides the best fit in travel-time of predicted arrivals to an empirically determined path anomaly.

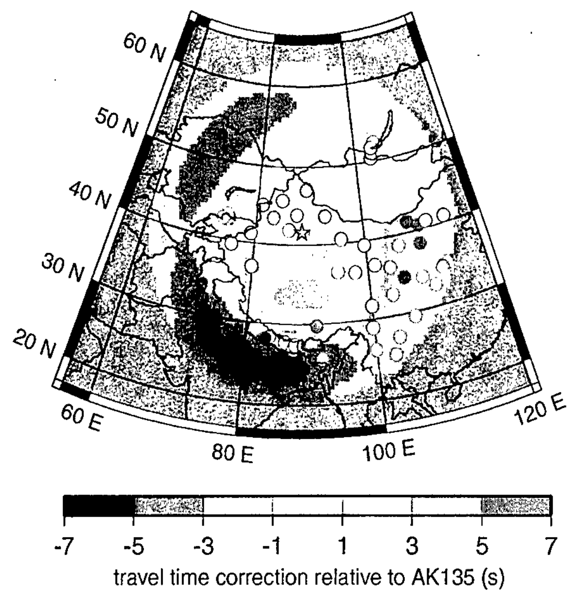

Figure 3-8. Cluster-centered Pn and P phase travel-time correction surfaces (relative to AK135) for Lop Nor compared with the empirical station path anomalies. The colored contours are the predictions from the 3-D CUB model referenced to the travel time from the 1-D model AK135. The symbols are the empirical phase path anomalies, color-coded similarly to the model predictions.

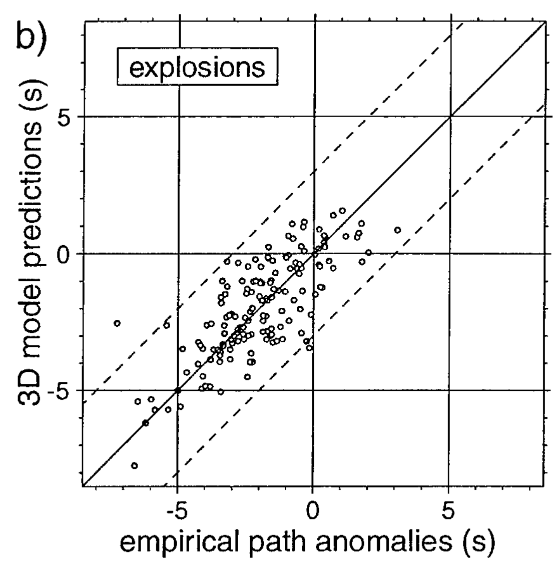

Figure 3-9. Overall comparison between the P and Pn travel times predicted by the CUB model and the empirical station path anomalies for explosion clusters studied. Results are presented only for regional phase data (epicentral distance less than 20 degrees). The empirical station path anomalies are on the horizontal axis and the 3-D model predictions on the vertical axis.

3.4 Model Validation – Relocation.

The location procedure is based on a grid-search, in which the rms misfit of predicted to observed travel times is the functional minimized (Levshin and Ritzwoller, 2002). Epicentral latitude and longitude are the two unknowns searched across a spatial grid. The third unknown, origin time, is found for each trial location by minimizing the rms residual. Event depth is fixed to the ground-truth value. Only first arriving mantle P phases at epicentral distances less than 20 degrees are used. The spatial grid is 1 X 1 km and covers 2500 square km. For each grid point, the difference between the observed and predicted time for each observation is found. Observations with residuals having absolute values above a certain threshold (3 s) relative to the starting location are discarded. The distance between the best spatial node (with minimal rms) and the ground truth location for a given event is considered as the relocation error. We find that for all GT5 cluster locations this preliminary validation test shows that the 3-D CUB model improves locations relative to locations based on the 1-D model AK135 in 70-85% of all cases, with details depending on the number of reported phases used for relocation. Typically, the 3-D model reduces the location errors to about half the values attained with the 1-D model.

SECTION 4

CONCLUSIONS

High-resolution cluster analysis is being applied to earthquake sequences and to some nuclear explosion sites in Asia and north Africa for which one or more of the associated events is known to an accuracy of 5 km or better (GT5). These analyses produce new locations (relative to the centroid of the cluster) and 90% confidence ellipses that in some cases, after shifting the centroid to best match reference event locations, sharpen the spatial relationship of earthquake sequences to known faults.

Our initial work with candidate "reference events" suggests that considerable care must be taken to ensure reliable results. Many aftershock studies and temporary seismograph deployments in remote areas suffer from logistical, operational, and analytical difficulties that may compromise the quality of the computed locations. Such problems are seldom apparent in published papers and abstracts. In many cases it will be necessary to gain access to raw data and analysis records—and most importantly, to gain the cooperation of the original researchers—to confirm the reliability of "reference events" offered by the seismological community in these regions.

The Hypocentroidal Decomposition method of cluster analysis has proven to be very well suited to the requirements of ground truth validation exercises. Cluster analysis has been applied to 23 earthquake and explosion sequences in Asia and north Africa for which one or more of the associated reference events is known to an accuracy of 10 km or better (GT10). After removing bias in the relative locations by shifting the hypcentroid to best match reference event locations, these analyses produce new absolute origin times and locations for all the events in each cluster that can be used to determine source-station phase path anomalies across the region. However, we have also found a number of areas in which additional development of the method is needed. For example, a more rigorous and systematic procedure (perhaps distance dependent) for matching the offsets in cluster event origin times to the corresponding reference event origin times needs to be developed.

Estimates of empirical station path anomalies derived by cluster analysis provide a valuable independent validation tool for assessing 3-D models of the region of interest. Moreover, cluster hypocenters that have had systematic bias removed can also be used as a validation tool by demonstrating that locations based only on regional arrival times using a 3-D model can significantly improve locations using a 1-D model. The CUB 3-D model appears to perform quite well under these evaluation metrics.

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